57-3

Proceedings of the American Academy of Arts and Sciences.

VOL. 57. NO. 3.—APRIL, 1922.

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Received October 7, 1921. Presented October 19, 1921.

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Introduction.

Under hydrostatic pressure the electrical resistance of most metals decreases. On the other hand the resistance of these metals increases under tension. There are, however, a few metals which are abnormal in that their resistance increases under pressure. It has been known for some years that bismuth is such a metal, and I have recently added to the number lithium, calcium, strontium, and antimony. It seemed to me of considerable interest to determine the effect of tension on the resistance of these metals. These data are presented in this paper. When I started this work, such measurements had not been published for any of these metals. During the course of my work, however, data were published in Italy for the effect of tension on the resistance of bismuth.[1] The resistance of this was found to decrease under tension, so that this metal is abnormal with respect to both tension and pressure. I have verified this result. I find that strontium is the only one of the remaining four which is also abnormal with respect

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1 E. Zavattiero, Rend. Accad. Lincei, 29 (1) 48–54, 1920.

to tension; the resistance of lithium, calcium, and antimony increases, as is normal, under tension.

When I started these measurements, only one metal was known which was abnormal with respect to tension; this was nickel. The measurements were made by Tomlinson [2] in 1876, on nickel which presumably had several per cent of impurity. Since it was my good fortune to obtain through the kindness of the Leeds and Northrup Co. some nickel of exceptionally high purity, I repeated the measurements of Tomlinson, and also extended them to find the effect of temperature and cyclic changes of tension. I have verified the sign of the effect found by Tomlinson, although there is not close numerical agreement, as was to be expected.

Since cobalt is in many respects closely related to nickel, I also determined the effect of tension on the resistance of it. The effects are entirely normal.

In addition to the five abnormal pure metals mentioned above, the alloys manganin and therlo are also abnormal with respect to their pressure coefficients. I have determined the tension coefficients of these also, and find them to be normal in sign, but to be very small.

My previous measurements of the pressure coefficient of resistance have suggested certain views as to the nature of the conduction mechanism.[3] In the following I shall discuss how far these new facts are in accord with these views.

This discussion demands a knowledge of Young's modulus. I have determined this for most of these metals.

Description of Method and Apparatus.

The apparatus and method were very simple, and for the most part were similar to those already adopted for the measurement of the effect of pressure.

The resistance was measured by a potentiometer method, the drop of potential between two potential terminals attached to the specimen being balanced against the drop due to the same current flowing through an appropriate combination of known resistances. The details of the apparatus were the same as those previously used in measuring the pressure coefficient, and have been fully described

2 H. Tomlinson, Trans. Roy. Soc. 174, 1–172, 1883.
3 P. W. Bridgman, Phys. Rev. 9, 269–289, 1917, and 17, 161–194, 1921.

elsewhere.[4] The wire under tension merely replaces the wire under pressure of the previous experiments.

The wires used were small, and a load of a few kilograms was sufficient in all cases. The wire was mounted vertically, and attached at the upper end to one arm of an equal arm balance, to the other arm of which known weights could be applied. For most metals it was most convenient to use the ordinary solid weights, but if there were hysteresis effects, as in the case of nickel, it was necessary to apply and remove the weight continuously; to accomplish this a water weight was used. In the case of antimony, because of its excessive fragility, a special arrangement was necessary which will be described in detail later.

The lower end of the wire was attached to a bracket, supported from above. This bracket, with the wire, dipped into an oil reservoir about 12 inches high and two inches diameter. The top and bottom of the reservoir were connected through side tubes with a turbine stirrer, by means of which a continuous stream of oil was maintained past the specimen. The wire itself was about 6 inches between potential terminals. In most cases the measurements were made at room temperature only, and the stirrer adequately maintained approximate equality of temperature. A correction could be easily determined and applied for the change in resistance due to drift of temperature of the oil bath. In a few cases, however, when more careful regulation of temperature was necessary, a large bath of water, maintained at constant temperature thermostatically, was raised around the oil bath. The walls of the latter were of thin brass, and exchange of heat between the oil and the water was sufficiently rapid to maintain constancy of temperature in the oil.

The magnitude of the tension applied was usually considerably less than the elastic limit. The behavior of the resistance gives a sensitive test of the perfect elasticity under the applied tension. The wire was usually seasoned by a number of applications of a tension higher than that of the final measurements. The behavior of the resistance beyond the elastic limit is complicated, and would make an interesting study on its own account. I felt this to be beyond the scope of the present work. I have, however, in nearly all cases determined at least the sign of the permanent change of resistance produced by exceeding the elastic limit, and in some cases have examined the phenomena a little more in detail. It appears that in all cases the permanent change of resistance beyond the elastic limit is an increase.

4 P. W. Bridgman, Proc. Amer. Acad. 52, 571–646, 1917.

For the theoretical considerations suggested by these measurements it is necessary to know the mechanical deformation produced by the tension, that is, to know Young's modulus. I have determined this for most of the metals. The metals were in most cases too soft to allow a direct determination by hanging a weight on the wire and observing the change of length, so that an indirect method was necessary. The method I used was that of flexure. A horizontal wire of known length and section was bent by a weight hung on the free end, and the amount of the flexure of the free end determined. From this Young's modulus can be calculated. The calculation assumes the perfect isotropy of the wire. It is probable that this condition is not always satisfied to as high a degree of approximation as would be desirable, but under the conditions it seemed the best that I could do. The modulus for manganin and therlo was determined directly.

The difficulties of the resistance measurements vary greatly for the different metals. The effect is in any event small, and for those metals which are soft and have a low elastic limit, the magnitude of the maximum effect is sometimes not greatly in excess of the order of magnitude of the accidental errors. An additional difficulty for the metals Li, Sr, and Ca is that of making electrical connections. These metals cannot be soldered, and mechanical spring clamps had to be used. The resistance at the contact would sometimes vary sufficiently to produce perceptible fluctuations in the main current, and also the potential terminals were sometimes subject to slight displacements under the stirring by the oil. The details of these difficulties will be described under the metals separately.

I am indebted to the skill of my assistant, Mr. J. C. Slater, for practically all the actual readings.

Here follows a description of the details for each metal.

Detailed Data for Individual Metals.

Lithium. The material was from Merck, for which I have no analysis. It was apparently entirely free from inclusions of slag, and mechanically homogeneous. Metal from the same lot was used in previous determinations of the pressure coefficient of resistance.[5] It was formed into wire of about 0.032 inches diameter by cold extrusion, in the usual way. The surface of the wire so formed is bright, and it

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[5] P. W. Bridgman, Phys. Rev. 56, 59–154, 1921.

remained bright throughout the course of the experiment. The oil of the bath, a neutral heavy white petroleum which is used for medicinal purposes, was without perceptible chemical action, at least at room temperature. The current and potential connections were maintained by mechanical contact, the potential connections by small spring clamps of special design.

The measurements of lithium were the most difficult of any, because of the extreme softness of the metal. Four sets of runs were made in all. The first two, made without the thermostat, established the sign of the effect and its probable magnitude. The last two runs, with the thermostat at 30°, were somewhat more satisfactory. The elastic limit is so low that I could not determine the linearity of the effect within the elastic range. There was permanent stretch under a load of 40 gm., and there were also irregular initial effects under the first few grams of load, which may have been due to straightening of the wire. All the best measurements were made between a load of 15 gm. as zero and 35 gm. The change of resistance under this maximum increase of load of 20 gm. is an increase of only 0.02%. The extreme variation of the individual determinations for the best specimen was in the ratio from 7 to 20. Twelve determinations were made. The probable error of the mean, calculated by least squares, was 6.7%.

The tension coefficient of resistance, that is the proportional change of resistance under a tension of 1 kg/cm^2 was $+4.9 \times 10^{-5}$ for the best specimen; the other run with the thermostat gave 4.6×10^{-5}, and the only one of the preliminary specimens which was worth computing gave 4.7×10^{-5}. In the following I shall assume for the most probable coefficient $+4.8 \times 10^{-5}$.

Young's modulus was determined from the bending of three specimens, of the diameter given above and approximately 7 cm. long. The maximum load applied to these specimens was 0.066 gm. Within the limits of error the displacement was proportional to the load. The values obtained for Young's modulus were respectively 4.72, 5.26, and 4.93×10^{10} Abs. C.G.S. units. Take as the most probable mean 4.9×10^{10} C.G.S. or 5.0×10^4 in kg/cm^2.

The cubic compressibility of lithium has been found by Richards [6] to be 9.0×10^{-12}, pressure expressed in Abs. C.G.S. units. This may be combined with Young's modulus by the formula of elasticity $\sigma = \frac{1}{2}\left(1 - \frac{E\kappa}{3}\right)$ to find Poisson's ratio. The formula gives 0.42. The

[6] T. W. Richards, Jour. Amer. Chem. Soc. 37, 1643–1656, 1915.

high value is in line with our other experience that a comparatively soft metal has a Poisson's ratio near 0.5.

Calcium. This material I owe to the kindness of the Research Laboratory of the General Electric Company. It was from a different batch than that whose pressure coefficient of resistance I have previously measured.[7] So far as any chemical analysis can detect, all the calcium of the General Electric Co. contains no impurity, but in my previous discussion I remarked on the fact that there was nevertheless some difference between different batches. Some of the material can be extruded easily, while the extrusion of other is difficult. The wire which I previously used was extruded with difficulty, and was inclined to be brittle. The present wire was extruded easily, and could be readily bent into a comparatively short radius. The wire as supplied by the General Electric Co. had been extruded to a diameter of about 0.055 inches. In order to better adapt it to the magnitude of the tension which I could readily apply, I drew it down through steel dies from this size to 0.030 inches, first scraping the surface bright under oil. I did not attempt to anneal it after this drawing. Another piece, whose behavior beyond the elastic limit was specially examined, was drawn to 0.019 inches. The breaking load was at the rate of 1200 kg/cm^2; it was the same for the two sizes of wire. The break takes place with very little elongation or reduction of area.

Measurements were made of the elastic rate of change of resistance on two different samples. The range of tension was not more than one fifth of the breaking load. The effect with this metal is large enough to allow good readings. Within the limits of error the change of resistance is linear with tension up to the stresses mentioned above. Readings were made at eight or ten different loads. The maximum departure of any single observation from a straight line was 5% of the maximum change for one of the specimens, and 4% for the other. The maximum change of resistance was 0.14% of the initial value.

The tension coefficient of resistance was $+ 8.24 \times 10^{-6}$ for one specimen, and 8.50×10^{-6}, tension in kg/cm^2, for the other. Take as the most probable value the mean $+ 8.37 \times 10^{-6}$.

Young's modulus was determined from the bending of two samples, whose dimensions were of the same order as those of lithium. The maximum load applied was 0.24 gm. Within the limits of error the bending was proportional to the load. One specimen gave for Young's modulus 2.080×10^{11}, and the other 2.065×10^{11}, in Abs.

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[7] Reference 5, p. 91.

C. G. S. units. Take as the average 2.07×10^{11} C. G. S., or 2.11×10^5, tension in kg/cm^2. Richards [6] has found for the cubic compressibility 5.7×10^{-12} Abs. C. G. S. Combined with Young's modulus by the formula of elasticity gives for Poisson's ratio the value 0.303.

There is a very considerable range of tension above that of perfect elastic behavior and below the breaking point where there are departures from linearity and hysteresis. The immediate effect of exceeding the elastic limit is to permanently increase the resistance. The wire may be seasoned for any particular range of tension beyond the elastic limit by repeated application and removal of the load. After seasoning, the resistance, as a function of tension, described hysteresis loops exactly similar in appearance to the familiar hysteresis loops of the relation between tension and elongation. The width of the loop in the extreme case of a tension just below the breaking point may amount to one third of the maximum change. This maximum change of resistance was 1.73% for one specimen, and 2.43% for the other. The average coefficient of resistance for the extreme hysteresis loop was 20.5×10^{-6} for one specimen, and 15.2×10^{-6} for the other, against a coefficient in the elastic range of 8.4×10^{-6}.

Strontium. This material was from the same lot as the specimen whose pressure coefficient of resistance was previously determined. I am indebted for it to Dr. B. L. Glascock. The probable purity, and some of its properties have been already discussed.[8] The metal was formed into wire by extrusion in the manner already described. Two sizes were used, 0.035 and 0.019 inches in diameter.

Two samples were used; the first was not geometrically perfect and did not give as good results as the second. Two series of measurements were made on the second. The diameter of this was 0.019 inches. The wire breaks without much preliminary yield at a load of about 800 gm. At a load of 700 gm. there was a very small permanent increase of resistance. The tension coefficient of resistance was determined through a range of 400 gm., readings being made at eight different loads within this range. The effect of tension is to *decrease* the resistance. Within the limits of error the relation between tension and decrease of resistance is linear. The maximum departure from the straight line of any single observed point was 7% of the maximum change. The maximum change of resistance was 0.14% of the initial resistance.

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[8] Reference 5, p. 96.

The tension coefficient of resistance given by the two runs on the better specimen was -8.2 and -8.4×10^{-6} respectively for a tension of 1 kg/cm^2. The other specimen, which was very much more uncertain in its indications, gave a coefficient of -10.5×10^{-6}. Take as the best mean -8.3×10^{-6}.

Young's modulus was determined from the bending of two samples. Measurements were also made on the sample of the imperfect resistance measurements, but these were discarded because of the uncertainty introduced by failure of geometrical regularity. The dimensions were approximately the same as for lithium. The maximum load was 0.066 gm. and within the limits of error the relation between bending and load was linear. The first specimen gave for Young's modulus 1.24×10^{11}, and the second 1.36×10^{11} Abs. C.G.S. units. Take as the best value 1.30×10^{11}, or 1.33×10^{5} when tension is expressed in kg/cm^2. The compressibility of strontium has never been determined experimentally so far as I am aware. A probable value for it may be found by interpolating in Richard's chart [9] giving the compressibility as a periodic function of the atomic weight. The value which I have assumed for the compressibility is 6.5×10^{-12} Abs. C.G.S. The value of Poisson's ratio computed with these values for Young's modulus and compressibility is 0.359. An error of 1% in the compressibility changes Poisson's ratio by 0.5%.

The behavior of the resistance beyond the elastic limit was not investigated, except to establish that there is a permanent increase in resistance on exceeding the limit. The permanent change is therefore of the opposite sign from the elastic change.

Antimony. So-called chemically pure antimony from the J. T. Baker chemical company was used. It was extruded into wire in the way previously described.[10] This wire is not from the same source as that whose pressure coefficient of resistance was previously measured, which was from Eimer and Amend. The present material has also been used in a determination of the effect of pressure on thermal conductivity, and the data will be given elsewhere.

Great difficulty was experienced with antimony because of its extreme brittleness, and a special procedure was adopted. At the suggestion of Mr. Slater, who made the measurements, the vertical position of the other metals was replaced by a horizontal position for antimony. The wire was placed in an oil bath, without a stirrer, resting on a massive bar of copper. Tension was applied by a spring

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9 Reference 6, p. 1649.
10 P. W. Bridgman, Phys. Rev. 9, 138–141, 1917.

balance connected to the antimony by a wire passing through a stuffing box in the side of the oil bath. This stuffing box was very loose, and was without appreciable friction. The current and potential terminals were soldered to the antimony wire. It is very difficult to make a soldered connection to this brittle material which shall be sufficiently in axial alignment to permit the application of an appreciable tension. The wires by which the tension was applied were cemented to the antimony wire by DeKhotinski cement.

Readings were made on three different samples; those on the first were the best. The diameter of the wire was 0.0146 inches. Three runs were made on it; the first two were rough in character and agreed within the limits of error with the third run. Within the limits of error the effect is linear with tension, and is positive, the resistance increasing with increasing tension. The maximum load applied to this specimen without rupture was 80 gm.; it broke at 90 gm. Readings were made at eight loads. The greatest departure from the straight line of any single observation was 8% of the maximum effect, which was a change of resistance of 0.025 %. The tension coefficient of this sample was $+4.5 \times 10^{-6}$ for 1 kg/cm^2 tension.

The second sample was extruded at a different time, and was excessively fragile. Its diameter was 0.024 inches, and it broke at a load of 20 gm. Only two readings were made; not enough to establish the linearity of the effect or to eliminate chance errors. The tension coefficient which would correspond to the mean of the readings with this sample was $+ 20.0 \times 10^{-6}$.

The third sample was 0.0295 inches diameter. It was much stronger mechanically than the second sample, and allowed loads beyond the elastic limit to be applied. The results were much less regular than for the first sample, however. Within the limits of error the effect is linear with tension up to a load of 140 gm. Ten readings were made; the worst of these departed from the smooth curve by 33% of the maximum effect. The tension coefficient shown by this sample was $+7.5 \times 10^{-6}$ for a tension of 1 kg/cm^2.

In estimating the most probable coefficient, the first sample must be given considerably more weight; I take as the most probable coefficient $+5.0 \times 10^{-6}$.

I have previously determined Young's modulus for antimony;[10] The value 7.8×10^{11} Abs. C. G. S. units was found. It was possible to definitely establish that the wire was not homogeneous, because the rigidity bears an impossible relation to Young's modulus. It is therefore not allowable to apply the formula of elasticity to compute

Poisson's ratio. The above Young's modulus, combined with Richard's value for the compressibility, 2.4×10^{-12} C. G. S.,[6] would give 0.18 for Poisson's ratio, which is improbably low. I shall in the following use 0.30, which is an average value for many metals, as more probably correct.

The third of the specimens above allowed some examination of the behavior beyond the elastic limit. Permanent increases of resistance were produced by loads in excess of 140 gm.; rupture took place at 270 gm. The phenomena were somewhat unusual in that there were no time effects. The permanent change of resistance under a given load assumed at once its final value, and there was no creep, as is usually the case. This does not seem very surprising in so brittle a material.

Bismuth. Measurements were made on three different grades of material, of three different grades of purity. The first was ordinary commercial metal, which has about 3% impurity. The second was electrolytic bismuth, for which I am indebted to the kindness of the United States Metals Refining Co. Analysis showed only 0.03% impurity of silver, and only traces of anything else. In spite of this very small impurity, however, the temperature coefficient of resistance is only about one half normal; apparently the silver exerts some very large specific effect. The third sample was electrolytic bismuth of my own preparation, which I had made several years ago for a determination of the pressure coefficient of resistance.[11] I have no chemical analysis, but spectroscopic analysis by Professor F. A. Saunders shows less impurity of silver than the other electrolytic bismuth. I was not able to repeat the preparation of this material, and had only a small quantity available. I verified the high temperature coefficient on the special piece used in this work. The question of the curious behavior caused by the small quantity of silver is more fully discussed in my paper on the effect of pressure on thermal conductivity.

Tension decreased the resistance of all the samples of bismuth. The effect is comparatively large, and with little care it was possible to obtain very good sets of readings, with deviations from the smooth curves by individual points of not more than 1%. The effects beyond the elastic limit are complicated. There is a very considerable initial range, however, within which the effect is linear, and there is no evidence for departure from the usual relations of perfect elasticity. The coefficients quoted in the following were determined within this range.

Three determinations were made on commercial bismuth at room

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11 Reference 4, p. 624.

temperature. The diameter of the wire was 0.028 inches, and the range of tension 300 gm. The coefficients found were -4.65, -4.54, and -4.78×10^{-5} respectively, the unit of tension being 1 kg/cm^2.

Measurements were made on one sample of the commercial electrolytic bismuth at two different temperatures. The dimensions of the wire, and the range of tension were the same as for the commercial material. At 31.1° the tension coefficient is -4.27×10^{-5}, and at 0.0° 5.20×10^{-5}. It is perhaps surprising that the coefficient should be lower at the higher temperature, but this is also the case with the pressure coefficient of resistance.

One set of measurements was made on my own pure electrolytic bismuth at 30°. The diameter of the wire was 0.0207 inches, and the range of tension 100 gm. Within this range the effect is perfectly linear, and no reading departs from the straight line by as much as 1%. The total change of resistance under this load was 0.13%. The tension coefficient of this sample was -2.92×10^{-5}. This is considerably less than the coefficients of the other samples, but will be accepted in the following as the best value for pure bismuth.

Young's modulus of my pure electrolytic bismuth was determined in the regular way by the bending experiments on two samples. The diameter was as above, and the length about 6.5 cm. The maximum load was 0.10 gm. The bending is linear with load within this range. The two samples gave for Young's modulus 2.29 and 2.45×10^{11} Abs. C. G. S. units respectively. This is much less than the value given in Kaye and Laby's tables, which is 3.19×10^{11}. It is of course possible that this wire is not homogeneous, like antimony. Richards [6] has found the compressibility to be 2.8×10^{-12}. Combined with my value for Young's modulus this gives for Poisson's ratio 0.39; combined with Kaye and Laby's value it gives 0.35.

The phenomena beyond the elastic limit are complicated and would be worth study for their own sake. In the first place, the resistance increases beyond the elastic limit, and hence the change is in the same direction as for other metals which are normal with respect to the elastic effect of tension. The time effects are very large, and may continue for many days under loads which are much below the breaking load and so small as to produce no marked change in the geometrical dimensions. Under a fixed constant load, the resistance increases at a time rate gradually becoming less, according to some law which I did not attempt to discover. Commercial electrolytic bismuth showed creep for two days under a load of 350 gm. whereas at 300 gm. the effects were still elastic. In these two days the initial rate of creep

had dropped to one quarter of its initial value, which was at the rate of an increase of resistance of $\frac{2}{3}\%$ per hour. After the removal of a load which has exceeded the elastic limit there are also time effects, not nearly so large in magnitude as the effects on applying load, but in the same direction; the resistance continues to increase for some time after the removal of load. In this particular the effect is like an ordinary elastic after effect.

Nickel. The sign of the pressure coefficient of this metal is normal; I have already mentioned in the introduction my reasons for repeating the measurements of Tomlinson. The metal was provided by the Research Laboratory of the Leeds and Northrup Co. in the form of bars approximately 6 cm. long, 1.5 cm. wide, and 3 mm. thick. I cut from this bar a piece of suitable dimensions, and drew it down in steel dies to 0.0101 inches. It was annealed after drawing by heating to redness.

The temperature coefficient of resistance between 0° and 100° was found to be 0.00634. This is higher than the highest previous value with which I am acquainted, 0.00618 by Fleming, and is evidence of the unusual purity.

Tomlinson had found that nickel is abnormal in two particulars. In the first place the resistance decreases under tension, and in the second place the decrease is not linear with tension, but passes through a minimum, so that at a tension of the order of two thirds of the elastic limit the resistance begins to increase with increasing tension.

I verified both these particulars of behavior, and made a few additional observations. If instead of increasing the tension steadily to the elastic limit, measuring the resistance as a function of tension on the way, as Tomlinson did, the wire is subjected to a seasoning for some fixed load by a number of applications and removals of the same load, and then a cycle of resistance measurements is made, it will be found that the decreasing measurements do not follow the increasing measurements, but an open hysteresis loop is described. This loop differs in one important particular from ordinary hysteresis loops. By hysteresis we usually mean an effect that for some reason lags behind. In this case, this would mean that with decreasing tension the resistances correspond to some greater tension on the increasing run. The curious fact here is that at the initial stages of the decreasing limb of the loop the resistance may be lower than that corresponding to any value of the tension on the increasing run. The mechanism of the loop must be something quite different from the ordinary hysteresis effects.

The range of tension through which the wire has been accommodated has a slight effect on the character of the loop; the tension of the minimum increases somewhat as the range is increased.

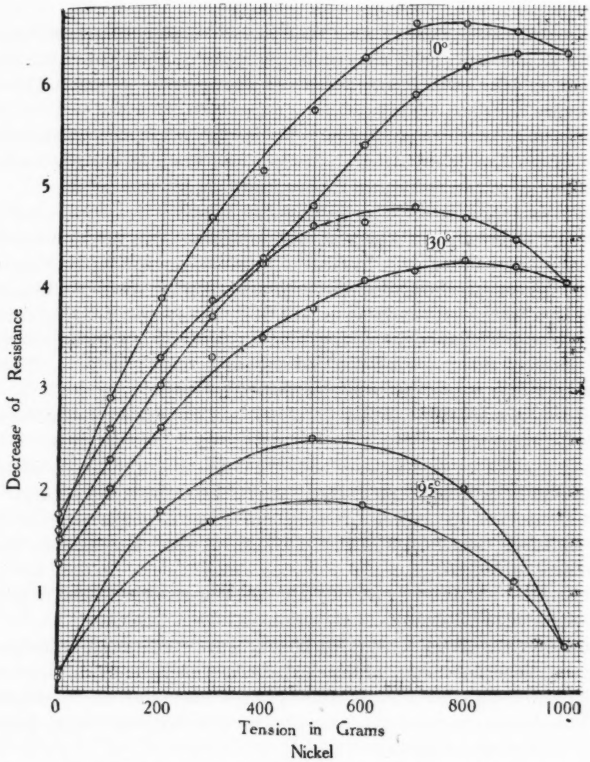

FIGURE 1. The decrease of resistance of Nickel in arbitrary units plotted against the tension in grams at three different temperatures. In each case the higher curve of the loop is that obtained with decreasing tension. One arbitrary unit of resistance corresponds to a decrease of 0.0345 per cent. The cross section of the wire was such that a load of 1000 gm. means 1900 km/cm².

There is a very large effect of temperature on the shape of the loop. I made measurements at 0°, 30°, and 95°. The minimum becomes

much flatter and moves in toward smaller tensions at higher temperatures. The initial magnitude of the change, for small alterations of tension, becomes larger at the lower temperatures. Here again we find a temperature coefficient with a sign the reverse of what we would expect.

The changes of resistance as a function of tension are reproduced in Figure 1. The range of tension is the same at the three temperatures, namely 1 kg., which corresponds to about 1900 kg/cm^2. This is not far below the elastic limit.

Cobalt. An examination of the behavior of cobalt was of interest because of its close relationship to nickel, and the abnormal behavior of nickel.

There was available a piece of the same cobalt wire, 0.0030 inches diameter, as that on which the previous determinations of the pressure coefficient of resistance were made.[12] It was annealed by heating to redness. Measurements were made to a maximum load of 100 gm.; the breaking load is about 180 gm. Within the range of 100 gm. the effect is normal with respect to sign, and the relation is perfectly linear within errors of the single readings of not more than 2 or 3%. There is no trace of the abnormal behavior shown by nickel.

The tension coefficient is $+9.94 \times 10^{-7}$ at 30°, the tension being measured in kg/cm^2.

Young modulus was not determined for this wire; because of the small diameter a special procedure would have been necessary. I shall in the following computations assume that it is the same as for iron and nickel, namely 2.0×10^{12} C. G. S. I shall also assume that Poisson's ratio is 0.30.

Manganin. The interest of this alloy lies in the fact that its pressure coefficient of resistance is abnormal in being positive.[13]

Determinations of the tension coefficient were made on samples from the same spool as that from which the pressure coefficient samples were obtained and from which the pressure gauges used in all my work were cut. Measurements were made on the wire in both the hard drawn and the annealed condition.

Three runs were made on the hard drawn specimen. The wire was 0.0054 inches in diameter. The breaking load was about 900 gm. The maximum load applied before the measurements was only 300 gm., and the runs themselves reached a maximum of only 250 gm. The wire was seasoned for this range of tension by a number of applica-

12 Reference 4, p. 607.
13 P. W. Bridgman, Proc. Amer. Acad. 53, p. 370, 1918.

tions and removals of 250 gm. The effect was found to be normal in sign, the resistance increasing under tension. The effect is smaller than for some of the pure metals, and accordingly was not so regular. The maximum departure of any of the observed points from a smooth curve was 4.5% of the maximum change. The relation between tension and change of resistance is very nearly linear, but there are nevertheless consistent small departures from linearity greater than the errors of measurement; the change becomes proportionally greater at the greater tensions. The average tension coefficient over the entire range of tension is not more than one or two per cent greater than the initial coefficient.

The three runs on the hard drawn sample gave the following values for the initial coefficient respectively: $+5.78$, 5.72, and 5.63×10^{-7} for a tension of 1 kg/cm^2. The average, $+5.71 \times 10^{-7}$, is taken as the most probably correct coefficient.

A length of wire contiguous to the hard drawn specimen was annealed by heating to redness. Measurements were made on the first application of tension. 250 gm. was distinctly beyond the elastic limit. The specimen was seasoned by several applications of 250 gm., and then by a number of applications of 200 gm., until finally the changes of resistance had become steady. The initial coefficient of the annealed wire was $+5.88 \times 10^{-7}$. After accommodation to the range of 200 gm. the coefficient had increased to 6.75×10^{-7}. This latter is the average coefficient over the range of tension. After accommodation the relation between resistance and tension is not linear or single valued, but the relation involves hysteresis of the usual character, the maximum width of the hysteresis loop being about 10% of the maximum effect.

Young's modulus of this wire was determined directly from the increase of length under a given load. A piece about 3.5 m. in length was hung in an elevator shaft, and observations made on fiducial marks at the top and bottom with microscopes. The supports of the microscope were entirely independent of the supports of the wire, so they could not be affected by the load applied to the wire. The hard drawn wire was used for this determination. It was seasoned by a number of applications of 500 gm.; the maximum load for the determination of the modulus was 400 gm. There was a slight amount of hysteresis, but there were no perceptible time effects. The maximum width of the hysteresis loop was 5% of the maximum extension. The mean of points with increasing and decreasing tension lie on a straight line within the limits of error, which were not more than 0.3%.

The value found for Young's modulus was 1.35×10^{12} Abs, C. G. S. or 1.39×10^{6} when the unit of tension is 1 kg/cm^2. Neither the coefficient of cubic compressibility nor any other of the elastic constants of manganin seem to have been determined. I shall assume in the following that a probable value of Poisson's ratio is $\frac{1}{3}$.

Therlo. This alloy is made by the Driver Harris Co., and is much like manganin in its properties. Its pressure coefficient of resistance is also positive,[14] and is very close numerically to that of manganin.

Measurements were made on both hard drawn and annealed wire, as for manganin. Two samples of hard drawn wire were used. The range of tension was 250 gm. The diameter of the wire was 0.005 inches. Within this range the relation between change of resistance and tension is sensibly linear; the departure from linearity shown by the manganin was not in evidence here. One run was made on the first sample; the coefficient found for it was $+ 4.32 \times 10^{-7}$ for a tension of 1 kg/cm^2. Three runs were made on the second sample, giving 5.19, 4.80, and 4.84 for the coefficient. I take as the most probable value for the coefficient $+ 4.8 \times 10^{-7}$.

A piece was annealed by heating to redness. Readings were made of the resistance during a long series of applications of tension, through a maximum range of 320 gm. The breaking load of the annealed wire is about 350 gm.; that of the hard drawn is over 1 kg. The initial coefficient for small loads immediately after annealing was 4.22×10^{-7}. After seasoning as above, this coefficient had risen to 4.60×10^{-7}. There seemed to be considerably less hysteresis in the relation between tension and resistance than in the case of annealed manganin.

Young's modulus was measured in the same way as that of manganin. There was considerably greater departure from linearity and more hysteresis than was shown by manganin, and much more of both than was shown by the resistance measurements. Seasoning was by the application and removal of 500 gm., and the modulus was measured over a cycle of 400 gm.

The hysteresis loop for this range of tension had an extreme width of 12% of the extreme extension. If we take the initial slope of this loop as giving Young's modulus, we find 1.41×10^{12} Abs. C. G. S., or 1.46×10^{6} in kg/cm^2. As in the case of manganin, I shall assume that Poisson's ratio is $\frac{1}{3}$.

The behavior of the resistance beyond the elastic limit is compli-

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14 Reference 5, p. 135.

cated, but there seems to be nothing essentially unusual about it. The permanent effect is an increase of resistance. There are also slow changes with time, both on applying and removing the load, as is normal.

Discussion of Results, excepting Nickel.

The results obtained above are collected into Table I, in which is given the tension coefficient of observed resistance, the pressure coefficient of observed resistance, the cubic compressibility, the reciprocal of Young's modulus, that is, the extension under unit load, Poisson's

TABLE I.

Metal	Tension Coefficient of Observed Resistance	Pressure Coefficient of Observed Resistance	Cubic Compressibility	Reciprocal of Young's Modulus	Poisson's Ratio	Tension Coefficient of Specific Resistance
Li	$+48.\times 10^{-6}$	$+6.8\times 10^{-6}$	9.2×10^{-6}	$20.\times 10^{-6}$	0.42	$+11.\times 10^{-6}$
Ca	+8.37	+10.1	5.8	4.75	0.30	+0.8
Sr	−8.3	+48.0	6.4	7.5	0.36	−21.2
Sb	+5.0	+11.0	2.4	1.25	0.30(?)	+3.0
Bi	−29.2	+15.5	2.8	4.2	0.37	−3.65
Mang.	+0.59	+2.31	0.7(?)	0.72	0.33	−0.60
Therlo	+0.42	+2.37	0.7(?)	0.69	0.33	−0.73
Co	+0.994	−0.90	0.6(?)	0.5	0.30	+0.19

ratio, and the tension coefficient of specific resistance. The unit of stress, whether of tension or pressure, for which the various coefficients is given is the kg/cm^2. By the coefficient of "observed resistance" is meant the change of resistance, per kg. per cm^2, of the wire as actually measured in the experiments, with fixed electrodes. Such a wire increases in length and decreases in cross section under tension, and decreases both in length and section under pressure. The coefficient of "observed resistance," when corrected for the changes of dimensions, gives the coefficient of specific resistance, that is the change of resistance of a unit cube. The tension coefficient of specific resistance is obtained by subtracting $(1 + 2\sigma)/E$ from the coefficient of observed resistance.

Since the mechanism of conduction is an affair of atoms and electrons, and since the number of atoms and electrons in a unit cube both change when the material is subject to tension or pressure, it does not

seem to me that there is a great deal of significance in the "coefficient of specific resistance." However, it is of interest to note in the table that the changes of dimensions of manganin and therlo are so large compared with the tension coefficient of observed resistance that the tension coefficient of specific resistance is negative, whereas the tension coefficient of observed resistance is positive. For the other metals the correction for change of figure is not large enough to change the sign of the coefficient of observed resistance.

It is in the first place to be remarked from the table that of the seven substances which are abnormal with respect to the sign of the pressure coefficient, only two, bismuth and strontium, are abnormal with respect to the sign of the tension coefficient. This would seem to indicate some essential difference between the conduction mechanism of these two substances and that of the others. Let us discuss what this difference may be in the light of the theory of metallic conduction which I have previously developed.

I have thought of conduction as due to a free path mechanism; the classical theory was a free path theory. The differences compared with the classical theory are these. In the first place, the free paths are thought of as long, because the free electrons are few in number. In normal metals, the paths of the electrons are to be thought of as through the substance of the atoms themselves. The path may be terminated when the electron makes the jump from one atom to the next. The chance of termination on making the jump will depend both on the amplitude of atomic vibration and the distance apart of the atoms. Now if the distance apart of the atoms varies little compared with the changes of amplitude, the variation of free path may be calculated in terms of the variation of amplitude only. The changes of amplitude, neglecting the effects due to changes of dimensions, may be calculated for changes of pressure and temperature, and so the change of path, and hence the changes of resistance may also be calculated. It is in throwing the entire burden of the variations on the free path, and in the method of computing the changes of the free path, that my theory differs mathematically from the classical theory. Now as a matter of fact, the changes of dimensions under changes of temperature are very small compared with the changes of amplitude, and the calculated changes of resistance agree well with the observed changes. Under changes of pressure the changes of dimensions are several fold larger, but still are so small compared with the changes of amplitude that an important part of the pressure coefficient may be computed. There is left an outstanding effect depending on

the changes of dimensions. The precise value of this effect cannot be computed without a more detailed picture of the entire mechanism than we have at present, but we can at least see what its sign is; as the atoms are compressed more closely together there will be less difficulty for the electrons to make the leap, and the mean free path, and so the conductivity, will increase.

So much for the mechanism in the case of normal metals. This picture would lead us to expect a decrease of resistance with increasing pressure, as is normal. To explain the behavior of those abnormal metals whose resistance increases under pressure I believed that there might be two possibilities. In the first place there might be such abnormalities in the law of force between the atoms that the amplitude of vibration increases as the atoms are brought closer together, instead of decreasing as normal. I thought that this was probably the case with bismuth, and suggested that the same abnormality would explain the increase of volume on freezing. For such a metal the paths of the electrons are still to be thought of as through the substance of the atoms, and the interference with the free path to take place on making the jump from one atom to the next. A second possibility I thought to explain the behavior of lithium. Here the electrons occupy spaces in a lattice between the atoms, and conduction consists in motion of the electron lattice through the atomic lattice. This is similar to the view of Wien [15] and Lindemann [16] as to the general character of conduction; I believe that this can be the mechanism only in exceptional cases. The effect of pressure on such a mechanism is to constrict the channels between the atoms through which the electrons pass. A simple calculation will show that the constriction of the channels due to change of distance between atomic centers is much more than the opening of the channels due to decreased amplitude of atomic vibration. Hence the pressure coefficient of resistance of such a substance would be expected to be positive, as it actually is. With regard to the other abnormal metals,[17] I did not have any positive basis for deciding to which type calcium and strontium belong, although I expressed my belief that probably calcium belonged to the lithium type, and I believed that antimony belonged with bismuth on the basis of its expansion on freezing.

Since publishing my pressure data, the crystalline structure of cal-

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[15] W. Wien, Columbia Lectures, 1913, 29–48.
[16] F. A. Lindemann, Phil. Mag. 29, 127–140, 1915.
[17] Reference 3, p. 183.

cium has been determined,[18] and this gives very strong probability to the view that its mechanism is also of the lithium type. It has been found that in metallic calcium the atoms of Ca occupy almost exactly the same positions as the Ca atoms in Ca F_2, the F atoms have merely dropped out of the structure. The inference is strongly suggested that the F atoms have been replaced by electrons, which do not give an X-ray photograph because of their small mass, and that therefore metallic calcium consists of interpenetrating lattices of atoms and electrons.

Let us now consider what these pictures of the mechanism lead us to expect for the tension coefficient. It is in the first place evident that we would expect the resistance of normal metals to increase in the direction of stretch, both because the distance between the atoms increases in this direction and because the amplitude of vibration in this direction increases to compensate for the decrease in period due to the weakening of the restoring force on the atoms due to their increased distance apart. A detailed working out of the theory must recognize in addition that changes in the positions of the atoms transversely may affect the period longitudinally. Now of course it is a fact that the resistance of normal metals increases in the direction of a tension. The same reasoning would lead us to expect a decrease of resistance in a direction transverse to the tension, and this also agrees with the facts in the few cases known.

Consider now bismuth. As tension is applied, the distance between the atoms increases longitudinally. The same abnormality in the force that compels an increase of amplitude when pressure is applied now compels a decrease of amplitude, and just as in the case of pressure the increase of amplitude causes a greater increase of resistance than can be overbalanced by the decrease due to the approach of the atoms, so now the decrease of resistance due to decreasing amplitude more than overbalances the increase due to the increasing separation of the atoms. The outstanding effect will be a decrease of resistance, which is actually the case.

It is otherwise, however, for metals of the lithium type. The resistance is here determined by the channels between the atoms. When a tension is applied, the channels are made narrower, because of the lateral contraction, just as they are made narrower when a hydrostatic pressure is applied, and we should expect an increase of resistance. This is actually the case for lithium.

The fact that the resistance of calcium increases under tension

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[18] A. W. Hull, Phys. Rev. 17, 42–44, 1921.

hence means that its mechanism is the same kind as that of lithium, and verifies the evidence from crystalline structure. The positive coefficient of antimony indicates the same thing. In this regard it may be said that recent work has cast considerable doubt on the reality of the supposed expansion when antimony freezes,[19] so that my former expectation would now lose its chief ground for support. Also against my former argument I may mention that there is a polymorphic transition of antimony at 135°, which I had previously failed to take into account. Even if the relations are abnormal for the modification which is stable up to the melting point, there seems no reason why we should expect the same abnormalities in the other modification, which is stable at room temperatures.

Strontium seems to require special consideration. Its tension coefficient is not abnormally high numerically; it is nearly the same as that of calcium, and much less than that of lithium or bismuth. On the other hand its pressure coefficient is unique in being at least three fold greater than that of any other abnormal metal. It seems reasonable to suggest that the mechanism of conduction in strontium may be a combination of both types. These would conspire to give an abnormally high pressure coefficient, and oppose each other, giving by difference a relatively small tension coefficient, of a sign which could not be predicted without further evidence.

These views of the conduction mechanism receive support from a numerical discussion. We confine ourselves to changes of resistance at constant temperature, that is to the changes under pressure and the longitudinal changes under tension. We assume that the change of resistance may be written down in terms of the changes of dimensions. The transverse and longitudinal changes of dimensions will affect the resistance in different ways, which are different for the two different types of mechanism. We write the equation

$$\frac{1}{R}\Delta R = k_l \frac{\Delta\delta_l}{\delta_l} + k_\tau \frac{\Delta\delta_\tau}{\delta_\tau}$$

where k_τ denotes the change of resistance per unit strain transverse to the direction of the current, k_l denotes the change of resistance per unit strain longitudinally, and $\Delta\delta_\tau$ and $\Delta\delta_l$ are the change in the transverse and longitudinal distance of separation of the atoms. Now if the strains are produced by tension, we have

$$\frac{\Delta\delta_l}{\delta_l} = \frac{\Delta T}{E}, \quad \frac{\Delta\delta_\tau}{\delta_\tau} = -\frac{\sigma}{E}\Delta T$$

[19] M. Toepler, Wied. Ann. 53, 343–378, 1894.

where ΔT is the tension; and if the strains are produced by pressure we have

$$\frac{\Delta\delta_l}{\delta_l} = \frac{\Delta\delta_r}{\delta_r} = \frac{1}{3}\cdot\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_\tau \Delta p\,.$$

Substituting these expressions for the strains gives

$$K_P = \frac{1}{3}\cdot\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_\tau [k_l + k_r]$$

and $$K_T = \frac{1}{E}[k_l - \sigma k_r]$$

where K_T is the tension coefficient of resistance tabulated above, and K_P is the pressure coefficient of resistance above. But since these two coefficients are known experimentally, we have two equations to determine the two unknowns k_l and k_r. I have made the calculations and tabulated the results in Table II.

TABLE II.

Metal	k_r	k_l
Li	−3.2	+1.0
Ca	−5.4	+0.16
Sr	−15.8	−6.7
Sb	−13.6	−0.1
Bi	−7.0	−9.6
Mang.	−7.3	−1.6
Therlo	−8.1	−2.1
Co	+1.92	+2.6

Let us now consider what sort of numerical values our theory would lead us to expect. For a normal metal we expect k_l to be positive, and greater than unity, since in addition to the increase of resistance brought about by increasing the distance apart of the atoms, there is an increase due to the simultaneous increase of amplitude. Since most of the electron paths have a transverse as well as a longitudinal component, the same reasoning would lead us to expect that k_r would also be positive and less than k_l, but of the same order of magnitude, there being two transverse degrees of freedom against one longitudinal. In the same way, we would expect that for bismuth, where the effect of

amplitude is abnormal in sign, and more than counterbalances the effect of changing distance between atoms, k_l and k_r should both be negative, and k_r less numerically than k_l. On the other hand, for those metals whose conduction mechanism is by the passage of electrons in channels between the atoms, we expect k_r to be negative, since increasing the transverse separation of the atoms decreases the resistance, and k_l to be relatively small. For strontium, which has a combination of both types of mechanism, we expect both k_l and k_r to be negative, k_r being numerically larger than k_l.

An inspection of the table shows that in every case these anticipations are strikingly verified, and the probable essential correctness of the theory receives strong support.

The values of the coefficients found for manganin and therlo indicate that for these the mechanism is for the most part like that of lithium, calcium, and antimony, but that there is in addition a small contribution by a mechanism of the bismuth type. Of course the phenomena for alloys are most complicated and varied in their types of behavior, but it is not difficult to picture to oneself that under some conditions when two different kinds of atoms crystallize side by side into the same space lattice that there should be channels left between the atoms for the passage of conduction electrons, or that the law of force between atoms of different kinds should show the same sort of abnormality that the atoms of bismuth show.

So far as I know there has been no previous attempt to make connection between any theory of conduction and the tension effects. In the light of the success of the above for abnormal metals it would now be of much interest to accurately determine the tension coefficients of the normal metals. If in addition the coefficient of transverse resistance could be determined, a most valuable check would be obtained, for we would then have three independent experimental coefficients, which must be expressible in terms of the two quantities k_l and k_r.

Discussion of the Effect in Nickel.

The peculiar nature of the phenomena for nickel makes it evident that there must be some unusual mechanism involved. It seems to me that there is probably an intimate connection with the polymorphic transition at 360°. Under a tension the transition temperature will be displaced by an amount proportional to the square of the tension, and if a certain function of the compressibility and Young's modulus has the right sign, the transition temperature will be

depressed. (The compressibility and Young's modulus which enter this relation have not been determined experimentally.) To explain the failure of a single sharp transition point, we invoke the same sort of mechanism that we suppose to be responsible for elastic hysteresis. Modern theories of the structure of metals explain elastic after effects and hysteresis by the fact that the microscopic crystalline grains are unequally exposed to changes of stress. Certain grains are unfavorably situated, and the elastic limit of these is exceeded before that of the average. Just these grains would first reach the transition point under an increase of tension, and other grains not until later. Thus the transition and also the change of resistance would not be expected to take place discontinuously at a single tension, but to be spread over a range instead. If now the resistance of the new phase is less than that of the original phase, we have a reason for the sign of the observed effect. The minimum of resistance with increasing tension is reached at that point where the rate at which new grains are being transformed has been so decreased by exhaustion that the decrease of resistance brought about by the transition is equalled by the increase of resistance due to the normal tension effect on the transformed grains.

This view of the phenomenon demands in the first place that the effect of tension be normal on that phase which is stable above 360°. So far as I know this effect has never been measured, but it would be going out of one's way to assume that it is abnormal. It is also demanded that the resistance of the high temperature phase when subcooled into the low temperature region be less than that of the low temperature phase, at least under the tensions which are found inside the grains. This again is subject for further experimental investigation. So far as I know, no measurements have been made on nickel of high purity. The measurements of Werner [20] are the only ones which I know with respect to the behavior of resistance through the transition point. I find from his data that the temperature coefficient of his hard drawn wire between 31° and 110° was 0.0041 of its value at 0°, and for soft wire the corresponding coefficient between 18° and 111° was 0.0054. The purest nickel should give under the same conditions a coefficient of about 0.0062. Werner finds no discontinuity in the resistance at the transition point, but does find a change in the direction of the curve with temperature. It is highly probable that there was actually a discontinuity, which was masked by the effect of impurity. It has almost always turned out that a phenomenon which

20 M. Werner, ZS. Anorg. Chem. 83, 275–321, 1913.

was at first thought to be continuous through a transition point is found, on increasing the purity, to be really discontinuous. It is true that the direction of the difference of temperature coefficients found by Werner is the reverse of that demanded by the above explanation, but in view of the extreme sensitiveness of the temperature coefficient to small impurities, I do not believe that a great deal of importance should be attached to this.

In support of the suggested explanation is in the first place the fact that neither iron nor cobalt show similar effects. These metals and nickel are similar in many respects, but are unlike in regard to their transitions. Cobalt does not have any polymorphic transitions, and the first transition of iron is at so much a higher temperature than that of nickel that it may well be without effect. The decrease of the tension of the minimum resistance of nickel with increasing temperature is also in accord with this view; at a higher temperature a smaller tension is necessary to make the transition take place. It is of course not possible to make any very exact numerical comparisons in view of the flatness of the minimum of the curves, but the data are at least not inconsistent with a depression of the transition point of a single homogeneous crystal by an amount proportional to the square of the tension. My explanation also demands that the resistance of the high temperature phase when it is subcooled be less than that of the low temperature phase. In view of Werner's failure to find a large discontinuity in the transition point, this probably means that the temperature coefficient of the high temperature phase is greater than that of the low temperature phase, and this is in accord with the fact that the initial rate of decrease of resistance with tension is less at high temperature than at low.

The abnormal character of the hysteresis loop on the falling branch is to be explained as follows. The primary effect of a tension is to force a transition from one phase to another. This transition would be expected to show hysteresis on reversing the direction of the change of tension. On the other hand, the sum of the pure tension effect in all the individual grains shows no hysteresis, because this is determined by the average tension, which is equal to the applied tension itself. Hence on decreasing the direction of the change of tension, the abnormal effects are decreased in magnitude, whereas the normal effects are unaltered. An application of this analysis to the upper end of the loop beyond the minimum of resistance (maximum on the diagrams) shows that on release of tension the resistance may drop to less than under any increasing tension.

Before this explanation can be finally accepted, experimental confirmation in several respects is required. Temperature measurements should be made on the high temperature phase above the temperature of transition. The resistance relations should be carefully studied in the neighborhood of the transition point for nickel of high purity. Finally it ought to be possible to recrystallize a wire by proper heat treatment so as to make it into a single large crystal. Under these conditions the character of the phenomena should entirely change. The initial effect of tension should be normal, and should continue so until a tension is reached so high as to force the transition to take place, when there should be a discontinuous drop of resistance greater in amount than the previous increase. Of course it is not obvious or necessary that the tension of this discontinuity be less than the elastic limit, and hence it may not be possible to realize it.

Summary.

The tension coefficient of resistance of lithium, calcium, strontium, antimony, bismuth, manganin, and therlo has been determined. These substances are all abnormal in that their pressure coefficients of resistance are positive. Young's modulus for these metals has also been determined. The tension coefficient for bismuth and strontium is found to be negative, but positive for the other five. In the discussion I have shown that these coefficients are in accord with my theory of resistance. The conduction mechanism of lithium, calcium, antimony, manganin, and therlo is on the whole "transverse," that of bismuth is longitudinal, and that of strontium is a combination.

The negative tension coefficient found by Tomlinson for nickel has been verified for nickel of high purity, and in addition the hysteresis effects and the effect of changes of temperature has been studied. Cobalt, on the other hand, is found to be entirely normal. It is suggested that the explanation of the abnormal behavior of nickel may be found in a depression by tension of the transition point normally at 360°.

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